Holistic Disaster Risk Evaluation for the Urban Risk Management Plan of Manizales, Colombia

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Abstract Disaster risk depends on both the physical vulnerability and a wide range of social, economic, and environmental aspects of a society. For a better risk understanding, a holistic or integrated perspective was considered when risk was assessed for the city of Manizales, Colombia. This assessment accounts not only for the expected physical damage and loss, but also for the socioeconomic vulnerability factors that favor second-order effects in a disaster. This comprehensive approach allows the identification of different aspects, related to physical vulnerability, social fragility and lack of resilience, that can be improved, thus enhancing integrated disaster risk management actions. The outcomes of this comprehensive assessment are currently being used as input to update the disaster risk management plan of Manizales.

Keywords Holistic risk assessment, Manizales (Colombia), probabilistic risk assessment, risk management plan, urban disaster risk index, urban resilience

1 Introduction

Disaster risk is defined as the potential economic, social, and environmental consequences of hazardous events that may occur in a given period of time. In order to evaluate risk according to this definition, the assessment should be interdisciplinary and multisectoral and should take into account not only the expected physical damage, the number and type of potential casualties or the economic losses, but also the conditions related to social fragility and lack of resilience that favor the second-order effects (indirect effects) that amplify the impacts when a hazardous event strikes an urban center.

A holistic risk assessment at the urban level needs to account for the vulnerability in several of its dimensions (physical, economic, social, educational, political, institutional, cultural, environmental and ideological), and requires combining the physical risk results with aspects that reflect the degree of social fragility and lack of resilience. Social fragility is measured by means of variables that try to capture issues related to human welfare, such as social integration, and mental and physical health, both at the individual and the community level. Lack of resilience is related to deficiencies in coping with disasters and recovering from them. In this framework, resilience is defined as the adaptive ability of a social-ecological system to cope and absorb negative impacts as a result of the capacity to anticipate, respond, and recover from damaging events.

The level of a disaster depends not only on the intensity of the natural event, but also on the

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vulnerability of the exposed elements. In the case of small-scale disasters, vulnerability is particularly important when the intensity of the hazard events is moderate or even low. In contrast, in the case of big disasters, vulnerability is quickly saturated due to the intensity of the hazards, and therefore, its relative importance is smaller (Cardona 2004a; Marulanda et al. 2010; Velásquez et al. 2014).

Disaster risk can be referred to as intensive risk when it is associated with high-severity, mid- to low-frequency hazardous events that involve large events—such as earthquakes, tsunamis, large volcanic eruptions, flooding in large river basins, or tropical cyclones—that are able to affect a significant number of exposed elements simultaneously. Extensive risk is associated with low-severity, high-frequency events, mainly but not exclusively related to highly localized hazards that usually affect a few communities at a time; in this case, the local and national emergency response mechanisms are effective (UNISDR 2009, 2011, 2013; ERN-AL 2011). Small disasters (related to extensive risk) are often the result of climate variability and the increase in social, economic, and environmental vulnerability. But they turn into a significant social problem because they destroy properties and livelihoods of the weak sectors of society and deepen their incapability to adapt, thereby perpetuating vulnerability and poverty (Velásquez et al. 2014).

From a holistic and comprehensive perspective, risk involves both the physical vulnerability and the social and economic vulnerability factors that configure the susceptibility conditions of urban areas. Physical vulnerability is related to lack of structural strength of the assets exposed to hazards, based on the potential intensities of the hazardous events in a period of time. The susceptibility of the social context depends on the socioeconomic fragilities and on issues related to lack of resilience of the population in the study area. Therefore, to reduce risk it is necessary to implement corrective and prospective actions against both hard and soft vulnerability factors. Consequently, disaster risk management requires an interinstitutional and multisectoral structure to implement, through public policies and actions, the changes needed to reduce vulnerability and disaster risk.

This article is focused on the holistic evaluation of the seismic risk of the city of Manizales, Colombia, and the results of a comprehensive risk assessment are used for updating the City Disaster Risk Management Plan.

2 Holistic Evaluation Methodology

Since 2001 the authors have been working on the holistic approach for disaster risk assessment and have developed and applied evaluation methodologies and metrics for this objective (Cardona 2001, 2004a, 2004b, 2011; Carreño 2006; Carreño et al. 2007b). The evaluation methodology has been improved and adapted according to the case studies and the availability of information related to hard (physical risk) and soft vulnerability factors (Barbat et al. 2010, 2011; Carreño et al. 2012, 2014a, 2014b; Birkman et al. 2013; Cárdenas et al. 2015; Jaramillo et al. 2016).

Carreño et al. (2007a, 2012) developed two alternative versions of the evaluation model—one based on indicators and the other based on expert opinions—in which risk assessment is performed by affecting the physical risk with socioeconomic factors or risk drivers, in order to reflect how socioeconomic fragilities and lack of resilience aggravate or amplify the direct effects of disasters. This holistic evaluation method has been implemented as a post-processing tool of the Comprehensive Approach to Probabilistic Risk Assessment (CAPRA) platform (Cardona et al. 2012; Salgado-Galvez et al. 2016). This approach contributes to the effectiveness of risk management, inviting to action through the identification of development weaknesses and shortcomings at the urban center (Carreño et al. 2007a).

Socioeconomic fragility and lack of resilience are described by a set of indicators that aggravate the physical risk. Thus, the total risk depends on the direct effects or physical risk, and the indirect effects expressed as a factor of the direct effects. Therefore, the total risk is expressed as follows:

$$R_T = R_F(1+F) \tag{1}$$

where R_T is the total risk index, R_F is the physical risk index, $(1+F)$ is an impact factor, and F is the aggravating coefficient. This coefficient depends on the socioeconomic fragility, SF, and on the lack of resilience of the exposed context, LR.

The physical risk, R_F, is evaluated using the following equation:

$$R_F = \sum_{i=1}^{p} F_{RFi} . w_{RFi} \tag{2}$$

where p is the total number of indicators related to the physical risk, F_{RFi} are the component factors and w_{RFi} are their weights. The physical risk factors, F_{RFi}, are calculated using the net values of physical risk indicators; they can be the result of a deterministic or a probabilistic risk assessment, such as the number of casualties, the value of destroyed area, the pure risk premium (that is, the relative average annual loss), and so on (Lantada et al. 2010). The weights are defined on the basis of local expert opinions processed by means of the Analytic Hierarchy Process (AHP) that is used to derive ratio scales from both discrete and continuous paired comparisons (Saaty 1980; Carreño et al. 2007a).

The indicators used in this evaluation have different characteristics and units, and transformation functions should be used to standardize the gross values of each indicator, transforming them into commensurable risk factors, taking a value between 0.0 and 1.0.

The transformation functions used in the methodology in order to calculate the hard and soft risk factors are membership functions for high levels of risk defined for each indicator in the terminology of fuzzy sets and logic (Carreño et al. 2007a). The value 0.0 represents the non-membership and 1.0 corresponds to total membership. The limit values, X_{min} and X_{max}, are defined taking into account expert opinions and information about previous disasters. Figure 1 gives a model for these functions.

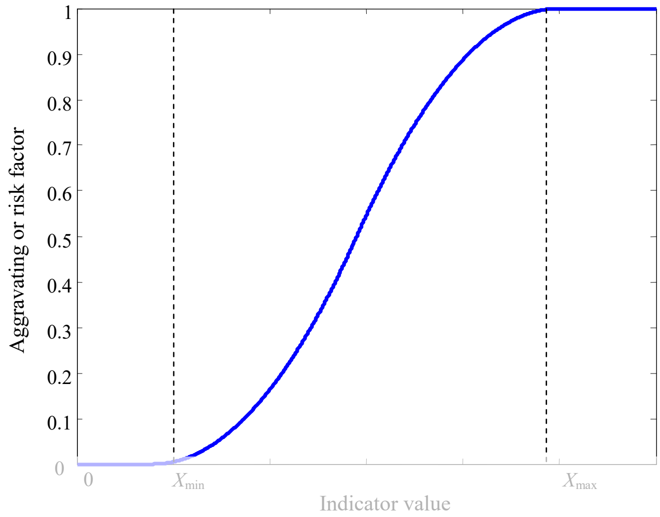

Fig. 1 Model for the transformation functions applied to calculate the hard and soft risk factors (Carreño et al. 2012)

Similar functions are used in the case of the indicators for social fragility and lack of resilience to develop the transformation functions. Sigmoid functions are used in most cases, and the type S or Z is used depending on the type of indicator. In the case of the indicators of lack of resilience, the function has an inverse (Z) shape, that is, higher values of the indicator result in lower values of aggravation. The aggravating coefficient is calculated in a way that is similar to computing the weighted sum of the aggravating factors.

$$F = \sum_{i=1}^{m} F_{SFi} \cdot w_{SFi} + \sum_{j=1}^{n} F_{LRj} \cdot w_{LRj} \qquad (3)$$

where F_{SFi} are factors related to the socioeconomic fragility, and F_{LRj} are factors related to the lack of resilience of the exposed context. The weights w_{SFi} and w_{LRj} represent the relative importance of each factor and are calculated by means of the AHP based on local expert opinions.

The indicators are selected, depending on the case study, as the most significant for each category. For example, in the case of social fragility, we can use the slum-squatter neighborhoods area, the mortality rate, the delinquency rate, and the population density. In the case of lack of resilience, the number of hospital beds, the health human resources, the public space area, the rescue and firemen manpower, the development level, and the emergency planning can be used. These indicators can be replaced by others according to the information available for each case study. There is not a minimum indicators number established to apply the methodology; instead, it is expected that the indicators involve information related to the social fragility and lack of resilience of the community. Jaramillo et al. (2016) provide an idea about indicators that can be used following the indicators applied by urban observatories of the United Nations and other social researchers.

The robustness of this methodology has been studied by assessing the uncertainty of values and the sensitivity to change of values, weights, and transformation functions. The methodology is not excessively sensitive to slight variations of the input data and to small changes in the modeling parameters, such as weights and transformation functions. If the range of variation of data and parameters is reasonable, the results of the numerical simulations will be stable and reliable. More details about the robustness analysis are given by Marulanda et al. (2009).

Detailed information about this evaluation method can be found in Carreño (2006), Carreño et al. (2007b), and Barbat et al. (2011). For management purposes, the risk assessment should improve the decision-making process in order to contribute to the effectiveness of risk management, calling for action and for identifying the weaknesses of the exposed elements and their evolution over time (Carreño et al. 2007a). In the case that the basic information required by this methodology does not exist or is not available, the holistic evaluation of the disaster risk can be performed by using expert opinions and applying an alternative methodology based on the fuzzy sets theory (Carreño et al. 2012, 2014a).

3 Holistic Evaluation of the Disaster Risk for Manizales

Manizales, with a population of 400,000 inhabitants, is located on the Colombian Central Mountain Range (part of the Andean Mountains, Cordillera de Los Andes) in the northern part of the Coffee-Growers Axis (*Eje Cafetero*). Due to this location, the city has an abrupt topography with steep slopes that has required public infrastructure for land stabilization in several areas of the city.

Manizales has been affected by various hazards in the past: landslides induced by rain, generated in most cases by the formation of settlements in areas with very steep slopes, as a product of the dispersed and uncontrolled growth of the city; floods, mainly on the banks of the Chinchiná river and Manizales, Olivares, and El Guamo creeks; ash fall events due to volcanic threat; and earthquakes. During the twentieth century the city was affected by six major earthquakes. This experience allows a better understanding of disaster risks for the decision makers and citizens in general. The city has been developing and consolidating its practices and public policies on integrated risk management for several years, especially since the 1970s.

This article is focused on the holistic evaluation of the disaster risk of the city of Manizales, Colombia, and how the results of the risk assessment have been used to update the City Disaster Risk Management Plan. The city of Manizales is subdivided into 11 districts (*comunas* in Spanish), which are the study areas for this evaluation: Atardeceres, San José, Cumanday, Estación, Ciudadela del Norte, Ecoturístico Cerro de Oro, Tesorito, Palogrande, Universitaria, La Fuente, and La Macarena. These districts do not have independent decision makers on disaster risk management, and they have strong differences among them that can be captured by this evaluation in order to focus efforts on different aspects that contribute to disaster risk. This evaluation was requested and funded by the local government. The results obtained by district are useful for the city administration in order to prioritize specific measures for each area in the city. It is expected that the local government will update this evaluation every four years to review the progress and effects of the different policies and measures in the city.

3.1 Physical Risk Index

A probabilistic approach was used for the analysis of seismic and landslide hazards (triggered by earthquakes or heavy rainfall) to obtain stochastic event sets suitable for the probabilistic loss estimation and risk results in terms of different metrics after aggregating in a rigorous way the losses associated to the different hazards. Detailed and high-resolution exposure databases were used for the building stock and infrastructure of Manizales, together with a set of vulnerability functions for each of the considered perils. The physical risk index, R_F in Eq. 1, is based on the results of this fully probabilistic multihazard risk assessment made for the city using the CAPRA platform (Bernal 2014; Bernal et al. 2017). Risk was assessed on a building-by-building basis, and by aggregating the metrics for the whole districts. Further details on the physical risk assessment can be found, as part of this special issue, in Bernal et al. (2017). For this evaluation, the selected indicators correspond to the pure risk premium (average annual loss / exposed reposition value) for six sectors: residential (*RF1*), commercial (*RF2*), industrial (*RF3*), health (*RF4*), institutional (*RF5*), and education (*RF6*). These values were standardized by using a transformation function that defines a value of 10‰ as the maximum pure risk premium for a risk factor of 1.0. Table 1 shows the obtained factors, the calculated weights for each factor, and the physical risk index for each district and for the city as a whole. The weights assigned to the risk factors are the same for all districts in the city.

Table 1 Physical risk factors for the different sectors; and physical risk index calculated for the districts of Manizales, Colombia

District	F_{RF1}	F_{RF2}	F_{RF3}	F_{RF4}	F_{RF5}	F_{RF6}	R_F
C1- Atardeceres	0.30	0.42	0.10	0.49	0.03	0.05	**0.25**
C2- San José	1.00	0.62	0.93	0.56	0.90	0.78	**0.80**
C3- Cumanday	1.00	1.00	1.00	1.00	0.51	0.68	**0.88**
C4- Estación	0.98	0.62	0.72	0.85	0.29	0.91	**0.75**
C5- Ciudadela del Norte	1.00	1.00	0.30	0.25	1.00	0.10	**0.61**
C6- Ecoturístico Cerro de Oro	0.97	0.28	0.37	0.18	0.28	0.89	**0.50**
C7- Tesorito	0.74	0.14	0.06	0.09	0.11	0.09	**0.23**
C8- Palogrande	0.92	0.78	0.87	0.25	0.70	0.62	**0.68**
C9- Universitaria	0.65	0.14	0.15	0.03	0.17	0.33	**0.25**
C10- La Fuente	0.94	0.92	0.86	1.00	0.17	0.66	**0.78**
C11- La Macarena	0.94	1.00	0.66	0.94	0.25	1.00	**0.81**
Manizales	0.93	0.87	0.36	0.70	0.49	0.59	**0.67**
Weight	0.20	0.15	0.15	0.20	0.15	0.15	1.00

Note: Physical risk factors for the different sectors: F_{RF1}= residential, F_{RF2}= commercial, F_{RF3}= industrial, F_{RF4}= health, F_{RF5}= institutional, F_{RF6}= education.

High physical risk occurs mainly in the residential and commercial sectors of the city. In order to make this evaluation useful for decision making, it is necessary to focus the attention on the obtained results for each district. In the case of the residential sector, the risk factor F_{RF1} takes values greater than or equal to 0.8 in most of the districts of the city (8 of 11) because the vulnerability of informal buildings. The districts San José, Cumanday, Estación, Ciudadela del Norte, and Ecoturístico Cerro de Oro reach the maximum value, or a value very close to it, due to the concentration of buildings built before the first seismic code (1984). Atardeceres has a low value of 0.30 for the risk factor in the residential sector. The risk factor for the commercial sector (F_{RF2}) shows greater differences between the districts of the city. Cumanday, Ciudadela del Norte, La Fuente, and La Macarena districts have values greater than 0.8. The districts of Tesorito and Universitaria have low values; these districts were built more recently applying seismic design codes. The risk factor for the industrial sector (F_{RF3}) also shows marked differences among the districts of the city. Only Cumanday has the maximum value because the buildings are older. San José, Palogrande, and La Fuente have values greater than 0.8 due to the lack of construction quality. Tesorito has a very low value (0.06), because this is a new area of the city.

In the case of the health sector (F_{RF4}), there are also large differences among the risk factors of the districts of the city. Two districts, Cumanday and La Fuente, reach the maximum value, while Universitaria has a value of 0.03 because most buildings in this area are earthquake resistant constructions. The physical risk factor for the institutional sector (F_{RF5}) takes the maximum value for the Ciudadela del Norte district. Four districts—Atardeceres, Tesorito, Universitaria, and La Fuente—have values below 0.2. In the case of the education sector (F_{RF6}), La Macarena is the only district that reaches the maximum value (1.0) because most buildings in that district are among the oldest, and Estación and Ecoturístico Cerro de Oro have values higher than 0.8. Atardeceres, Ciudadela del Norte, and Tesorito have the lowest values.

3.2 Aggravating Coefficient

Indicators related to social fragility and lack of resilience were identified to define the aggravating coefficient (F) and, therefore, the impact factor ($1+F$) of the potential physical damage and loss. They reflect the social absences, weaknesses, and susceptibilities from a development point of view that should be addressed by the processes of economic and social development planning to reduce vulnerability and risk from a comprehensive perspective. Table 2 shows the indicators related to social fragility (SF) and lack of resilience (LR) selected for the holistic evaluation, in accordance with the available information and the X_{min} and X_{max} parameters used in the transformation functions for each case. The indicators used to calculate the aggravating coefficient correspond to the official information provided by different agencies at the local and national levels such as: the Secretariat of Planning (*Secretaría de Planeación*), the Secretariat of Public Health and Legal Medicine (*Secretaría de Salud Pública y Medicina Legal*), the Risk Management Unit (*Unidad de Gestión del Riesgo*), the National Administrative Department of Statistics (*Departamento Administrativo Nacional de Estadística – DANE*), the System of Identification of Potential Beneficiaries for Social Programs (*Sistema de Identificación de Potenciales Beneficiarios de Programas Sociales – SISBEN*), and the National Planning Department (*Departamento Nacional de Planeación*) (Suarez 2015).

The indicators included in Table 2 were selected with the objective of involving the most representative information on the risk drivers of social fragility and lack of resilience, with complete coverage of the city areas, and the most updated information evaluated in a participatory way in the framework of the city program "*Manizales ¿cómo vamos?*" (Manizales, how are we doing?).

Table 2 Indicators for aggravating conditions (risk drivers of social fragility and lack of resilience) in the districts of Manizales, Colombia

	Indicator	Unit	X_{min}	X_{max}
X_{SF1}	Slum neighborhoods	% of the district area	5	30
X_{SF2}	Murder rate	Number of murders per 100,000 inhabitants	0	10
X_{SF3}	Persons without education	% of population	0	30
X_{SF4}	Overcrowding†	% of the disctrict area	3	30
X_{SF5}	Population density	People per square kilometer	4000	25,000
X_{LR1}	Hospital beds	Number of beds per 1000 inhabitants	0	30
X_{LR2}	Health human resources	Health professionals per 1000 inhabitants	0	15

X_{LR3}	Public space	% of the district area	1	15
X_{LR4}	Rescue human resources	Professionals per 10,000 inhabitants	0	7
X_{LR5}	Medium to high socioeconomic stratum	% of the district area	10	40
X_{LR6}	Community participation	Community Action Boards per 100,000 inhabitants	10	50

† Overcrowding is defined by SISBEN (2011) as tenement houses and dwellings with more than three people per bedroom.

Table 3 shows the results for the aggravating factors for each district of Manizales, taking into consideration the 11 indicators listed in Table 2. They have been obtained by using transformation functions type S (for social fragility) and Z (for lack of resilience) to standardize each indicator. The total aggravating coefficient (F) is obtained after scaling all the factors in commensurable units by using Eq. 3. Table 3 also shows the average values of the factors for the city, normalized with the density of population. The average values for the city recognize the murder rate, the lack of hospital beds, the lack of health human resources, and the lack of public space as the main aggravating conditions. But to guide decision making it is necessary to review the situation for each district.

Table 3 Aggravating factors and aggravating coefficient calculated for the districts of Manizales, Colombia

District	F_{SF1}	F_{SF2}	F_{SF3}	F_{SF4}	F_{SF5}	F_{LR1}	F_{LR2}	F_{LR3}	F_{LR4}	F_{LR5}	F_{LR6}	F
C1- Atardeceres	0.02	1.00	0.40	0.59	0.12	0.76	0.90	0.01	0.00	0.00	0.24	***0.37***
C2- San José	0.13	1.00	0.69	1.00	1.00	1.00	0.99	1.00	0.00	1.00	0.20	***0.74***
C3- Cumanday	0.00	1.00	0.27	0.19	1.00	0.98	0.99	0.92	0.06	0.73	0.94	***0.64***
C4- Estación	0.00	0.38	0.19	1.00	0.60	0.77	0.99	0.97	0.93	0.00	0.01	***0.53***
C5- Ciudadela del Norte	0.07	1.00	0.51	0.57	0.30	1.00	1.00	0.92	0.93	1.00	0.25	***0.69***
C6- Ecoturístico Cerro de Oro	0.00	0.99	0.26	0.26	0.05	1.00	1.00	0.00	0.00	0.10	0.90	***0.41***
C7- Tesorito	0.04	1.00	0.37	0.13	0.00	0.99	0.99	0.54	0.00	0.71	0.34	***0.47***
C8- Palogrande	0.00	0.30	0.27	0.00	0.01	0.99	0.99	0.98	0.00	0.00	1.00	***0.40***
C9- Universitaria	0.00	1.00	0.41	0.69	0.78	1.00	1.00	0.74	0.13	1.00	0.32	***0.65***
C10- La Fuente	0.45	1.00	0.46	0.60	0.99	1.00	1.00	0.77	0.32	0.82	0.01	***0.68***
C11- La Macarena	0.76	1.00	0.55	0.80	0.51	1.00	1.00	1.00	0.13	1.00	0.14	***0.72***
Manizales	0.16	0.92	0.43	0.52	0.70	0.96	0.99	0.81	0.24	0.70	0.34	**0.63**
Weights	0.09	0.09	0.1	0.09	0.09	0.09	0.1	0.08	0.09	0.1	0.08	1.00

Note: Aggravating factors due to different aspects. F_{SF1}= Slum neighborhoods, F_{SF2}= Murder rate, F_{SF3}= Persons without education, F_{SF4}= Overcrowding, F_{SF5}= Population density, F_{LR1}= Hospital beds, F_{LR2}= Health human resources, F_{LR3}= Public space, F_{LR4}= Rescue human resources, F_{LR5}= Medium to high socioeconomic stratum, F_{LR6}= Community participation.

The districts of San José and La Macarena show serious problems related to the social fragility and lack of resilience of the community, with the maximum contribution from the aggravating factors of murder rate, hospital beds, public space, medium to high socioeconomic stratum, population density, and health human resources.

The aggravating factor related to the slum area (F_{SF1}) is particularly relevant in La Macarena (0.76) and La Fuente (0.45), while in the other districts of the city it has values lower than 0.15. The aggravation due to the rate of murders (F_{SF2}) in the districts of the city is very close to the maximum value for most of the districts (9 of 11); this reflects social deterioration and breakdown in most parts of the city. The aggravation related to the lack of education of the population (F_{SF3}) for San José is the worst value in the city (0.69). Atardeceres, Ciudadela del Norte, Universitaria, La Fuente, and La Macarena, present values greater or equal to 0.40.

The values for the aggravating factor due to overcrowding of the population (F_{SF4}) show higher values in the districts of San José (1.00) and La Macarena (0.80). The lower values of this factor correspond to the districts Cumanday, Ecoturístico Cerro de Oro, Tesorito, and Palogrande. The aggravation related to the population density (F_{SF5}) shows values equal to or very close to the maximum value (1.0) for the districts San José, Cumanday, and La Fuente.

The aggravating factor related to the lack of hospital beds (F_{LR1}) has the worst values, very close to the maximum value for most of the districts (9 of 11). Atardeceres and Estación have lower values, although they are not negligible. The lack of hospital beds is an aspect that should be improved for the whole city. The lack of health human resources (F_{LR2}) is similar to the lack of hospital beds. Most of the districts have the maximum value or very close to it, except Atardeceres (0.9). The contribution of the lack of public space (F_{LR3}) has values greater than 0.8 for 6 of the 11 districts (San José, Cumanday, Estación, Ciudadela del Norte, Palogrande, and La Macarena). The lack of public space does not represent a problem for Atardeceres and Ecoturístico Cerro de Oro. The aggravation due to the lack of rescue human resources (F_{LR4}) has very low values. Only Estación and Ciudadela del Norte have high values that a significant lack of resilience.

The districts San José, Ciudadela del Norte, Universitaria, and Macarena show the highest level of aggravation with respect to level of development (F_{LR5}). Atardeceres, Estación, and Palogrande show no problem in this area. In contrast, Palogrande is the only district that presents the maximum value of aggravation in the area of community participation (F_{LR6}); Cumanday and Ecoturístico Cerro de Oro also have high values of aggravation. The other districts of the city have values lower than 0.35. Estación and La Fuente show no aggravation due to lack of community participation.

It is also possible to compare the different factors within each district. This is useful for identifying the contribution of each factor to the total risk of each district and for prioritizing the alternative risk reduction actions.

3.3 Evaluation of the Total Risk

The composite total risk index (R_T) is calculated based on the component indicators. It has been used as the Urban Disaster Risk Index (UDRi) for each district of the city, like it has been evaluated for other cities worldwide (Suarez 2007; Marulanda et al. 2009, 2013; Khazai et al. 2015). Figures 2, 3, and 4 show the results for the eleven districts, taking into consideration the physical risk, the aggravating coefficient, and the total risk, respectively. The figures show how the physical risk map values (Fig. 2) are amplified by the aggravating coefficient (Fig. 3), and result in the total risk or the UDRi (Fig. 4). All ranges of physical risk, the aggravating factor, and total risk were defined with officers and advisors of the Secretariat of Planning, taking into account the disparity and social characteristics used in the city to rank and compare the districts.

The aggravating coefficient (Fig. 3) shows medium-high values for the districts of San José, La Macarena, Ciudadela del Norte, and La Fuente; medium values for the districts of Universitaria,Cumanday, and Estación; medium-low values for Tesorito, Ecoturístico Cerro de Oro, and Palogrande; and a low value for Atardeceres.

The total risk (Fig. 4) shows high values for the district of Cumanday; medium-high values for La Macarena, San José, and La Fuente; medium values for Estación, Ciudadela del Norte, and Palogrande; medium-low values for Ecoturístico Cerro de Oro and Universitaria; and low values for Atardeceres and Tesorito.

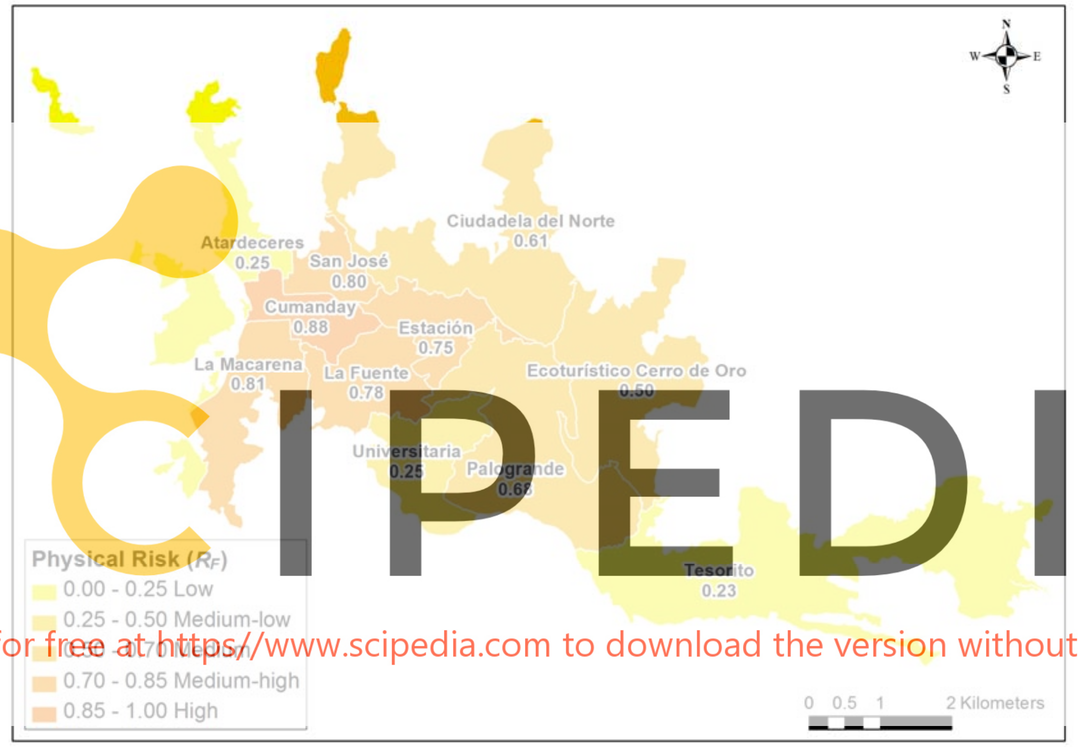

Fig. 2 Physical risk index R_F, based on seismic hazards and landslides due to earthquakes and rain, for the districts of Manizales, Colombia

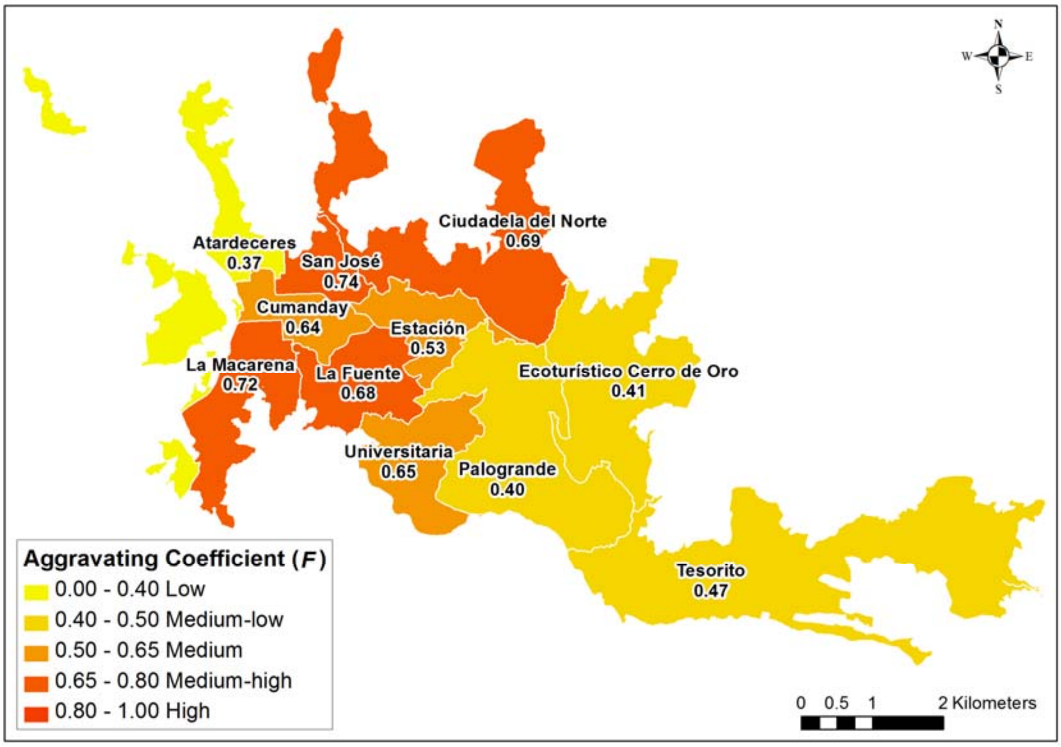

Fig. 3 Aggravating coefficient *F,* based on socioeconomic and resilience factors for the districts of Manizales, Colombia

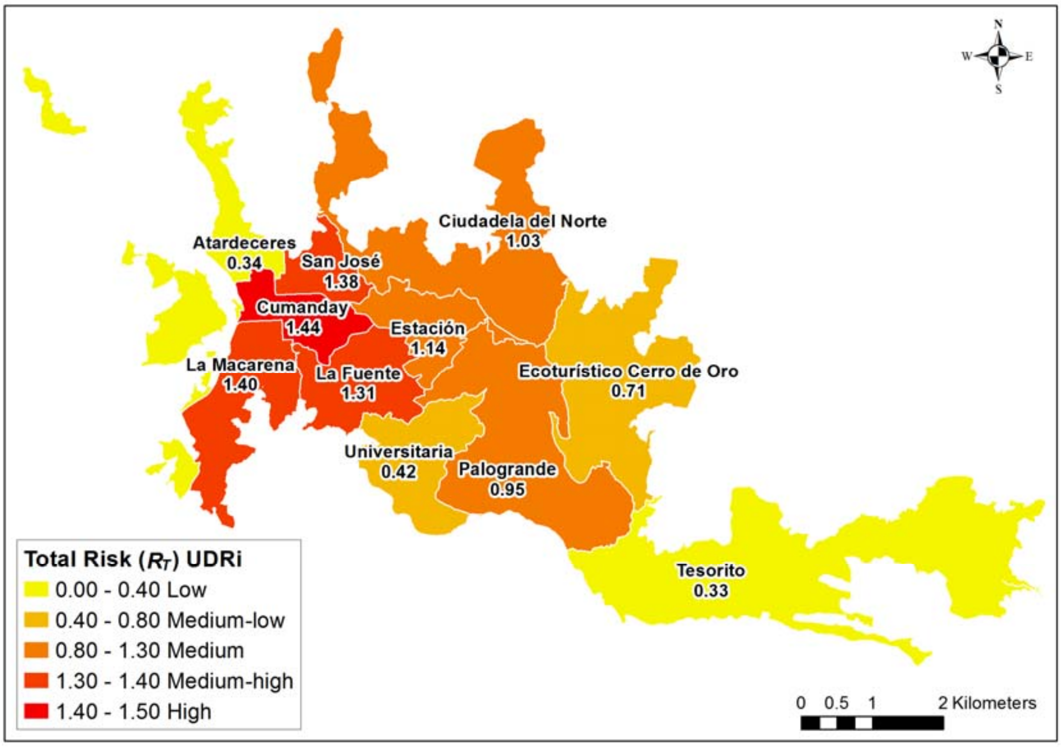

Fig. 4 Total risk index R_T, or UDRi, for the districts of Manizales, Colombia

Once the results and the ranking of risk in Manizales have been obtained by district, it is possible to review each case and disaggregate it into its components, identify which factors and indicators are more relevant, and define the possible actions to reduce the underlying causes of risk. The UDRi results for Manizales were analyzed for each district. Carreño (2015) provides detailed information related to the evaluation process and to the obtained results for the holistic evaluation of disaster risk, including the analysis for each district in the city.

Cumanday (C3) shows high total risk and high physical risk, illustrated by the levels of probable losses for the industrial, health, institutional, and educational sectors. It is the oldest area of the city. In the case of the aggravation, the most problematic factors are the murder rate, population density, lack of hospital beds, lack of human resources in health, lack of public space, and lack of community participation.

La Macarena (C11) presents high total risk and a high physical risk in the education, commercial, residential, and health sectors. The aggravation is mainly associated with the murder rate, the lack of hospital beds, the lack of human resources in health, the lack of public space, and the low level of development.

San José (C2) shows high to a medium-high level of total risk, the same level for physical risk and aggravation. Physical risk is high in the residential, industrial, and institutional sectors. The factors that amplify risk are the murder rate, population density, lack of hospital beds, lack of human resources in health, lack of public space, low level of development, and overcrowded tenant houses.

La Fuente (C10) shows a medium-high level of total risk due to medium-high values of physical risk and the impact factor as a result of the level of aggravation. Specifically, the district presents a high physical risk for the health, residential, commercial, and industrial sectors. The aggravation is mostly related to the murder rate, population density, lack of hospital beds, lack of human resource in health, and the level of development.

Estación (C4) presents a medium level of total risk obtained from a medium-high level of physical risk and a medium aggravation level. The physical risk is high for the residential, education, and health sectors. Aggravation has the greater contributions from the lack of human resources in health, the lack of public space, and the lack of rescue human resources.

Ciudadela del Norte (C5) shows a medium level of total risk resulting from a medium level of physical risk and a medium-high aggravation. Specifically, the physical risk is high in the residential, commercial, and institutional sectors. The conditions related to the greatest aggravation are the murder rate, lack of hospital beds, lack of human resources in health, level of development, lack of rescue human resources, and public space.

Palogrande (C8) presents a medium level of total risk resulting from a medium level of physical risk and a medium-low aggravation. Specifically, it presented a high physical risk for the residential and industrial sectors. The aggravation is mostly related to the lack of hospital beds, lack of community participation, lack of human resources in health and public space.

Ecoturístico Cerro de Oro (C6) shows a medium-low total risk level, resulting from a medium physical risk level and a medium-low aggravation. The physical risk is mostly due to the residential and education sectors. The aggravation is mainly related to the lack of hospital beds, lack of human resources in health, the homicide rate, and the lack of community participation.

Universitaria (C9) presents a medium-low total risk level, as the result of a medium-low physical risk and a medium-high aggravation. Specifically, the physical risk is identified for the residential sector. The aggravation is related to the homicide rate, the lack of hospital beds, lack of human resources in health, and the level of development.

Atardeceres (C1) shows a low level of total risk resulting from a medium-low physical risk and a low aggravation. A medium-low physical risk is identified in the health and commercial sectors. The aggravation shows a high level in relation to the murder rate and the lack of human resources in health.

Tesorito (C7) presents a low total risk, resulting from a low physical risk and a medium-low aggravation. Specifically, a medium-high physical risk is identified in the residential sector. The aggravation is related to the murder rate, lack of human resources in health and lack of hospital beds.

4 The Urban Disaster Risk Management Plan of Manizales

The Urban Disaster Risk Management Plan is the legal instrument, according to Law 1523 of 2012, through which the objectives, goals, strategies, actions, and actors are defined to implement the national policy of risk management of Colombia, during a period of 12 years (2016–2028, three administrations). Figure 5 presents the main programs and subprograms for the city of Manizales, within the framework of the risk knowledge, risk reduction, and disaster management processes.

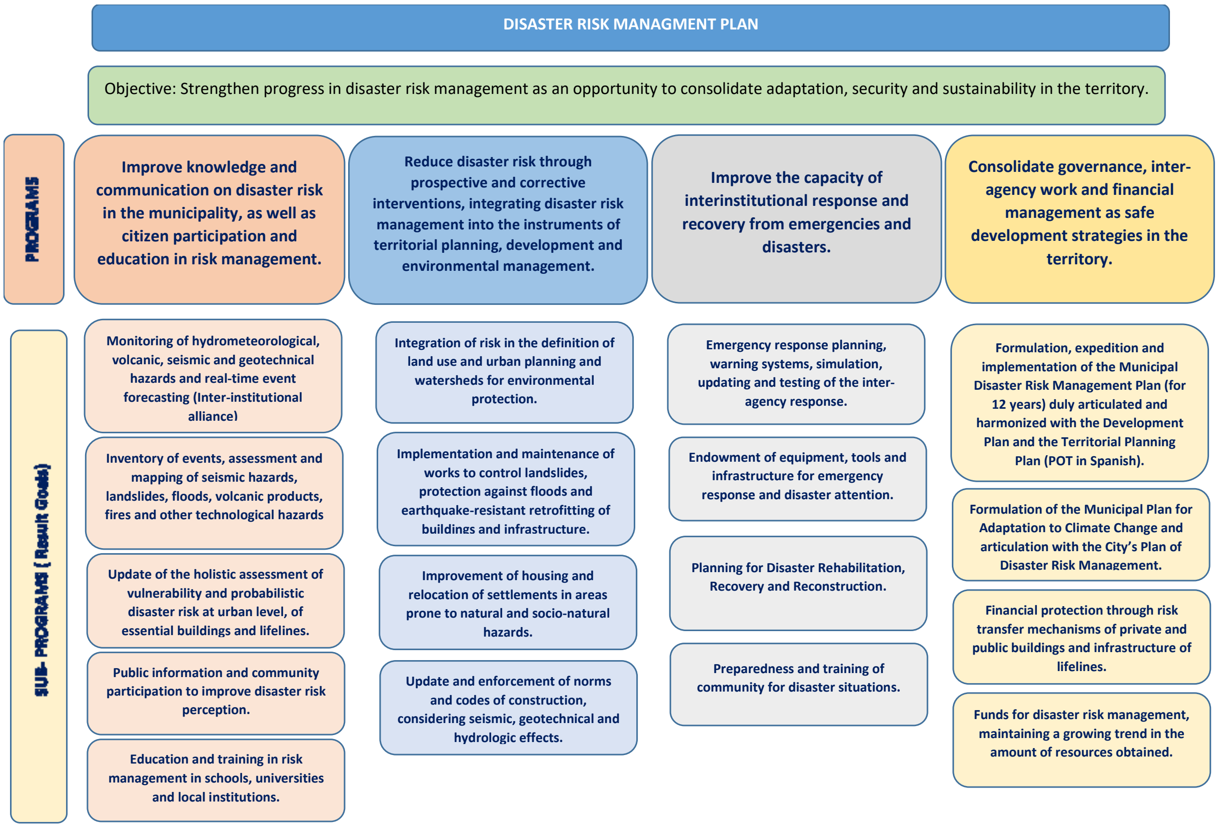

Fig. 5 Programs and subprograms of the Disaster Risk Management Plan of Manizales, Colombia *Source* Alcaldía de Manizales (2016a).

This municipal plan was adopted by decree (Alcaldía de Manizales 2016a) to define the medium- and long-term actions, derived from the general diagnosis of the city through the physical and holistic assessment of the disaster risk, and the evaluation of the disaster risk management performance in the city by using the Risk Management Index (RMI) (Carreño et al. 2004, 2007a), both in retrospective and prospective ways. It also defines the goals, the general procedures, and mechanisms for achieving them, the budget, and the schedule of all activities. The strategic and programmatic components of the plan have been the result of a participatory process, in which it was possible to systematize contributions from the different public and private stakeholders and actors, who attended different workshops and interagency meetings. Both general objectives for the whole city and specific objectives by districts of the city have been defined, using the results of the holistic disaster risk assessment described above. In addition, the holistic risk assessment has been included in the plan as a recursive process and continuous risk research, facilitating the dynamic and adaptive management by risk problem framing and reframing.

This plan was incorporated into the socioeconomic Development Plan of the current administration (2016–2019) as a component of environment, climate change, and disaster risk management and will guide the action to reach the development objectives and goals and the instruments of linkage and harmonization with other plans at the city level, such as the territorial or land-use planning (POT, *Plan de Ordenamiento Territorial*, in Spanish) and the emergency response plan of the city (Alcaldía de Manizales 2016b).

5 Conclusion

Risk understanding is an unavoidable process and early step for risk management. The formulation of a policy and process for risk reduction and of adaptation should be based on knowledge of the components and the disaggregation of the underlying causes of vulnerability and risk, taking into account both their harder and softer characteristics. Holistic risk assessment has been developed to deal with these characteristics, considering the physical risk, or potential direct effects, and its amplification, or potential indirect effects. This type of integrated and scientific approach facilitates decision-making and the flexible adjustment in practice of actions to be implemented by different actors as a disaster risk management plan.

The Disaster Risk Management Plan of Manizales, Colombia, has been formulated based on the participation of the different private and public actors and with the input from the holistic disaster risk assessment of the city. Strategic and programmatic components have been defined, framing and reframing the risk problem, and identifying the main actions to be implemented in each district of the city and making the follow-up of risk reduction in a dynamic way, using the holistic risk assessment approach to give account of the improvements and achievements on vulnerability and risk reduction.

The results for the city of Manizales can be compared with those obtained for other cities following the same methodology. But, for such a comparison, it is necessary to take into account that the indicators involved in the evaluation can change according to the existent and available information in each case. The objective of this holistic approach is to support the decision-making process on disaster risk reduction by improving the risk understanding of the stakeholders; the comparison with other cities can provide a general idea of the situation, but the real value of this evaluation is in the identification of differences at local level.

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References

Alcaldía de Manizales. 2016a. Municipal plan for disaster risk management of Manizales (*Plan municipal de gestión del riesgo de desastres del municipio de Manizales*). Decree 415, 23 August 2016 (in Spanish).

Alcaldía de Manizales. 2016b. Municipal strategy for emergency response of Manizales (*Estrategia municipal para la respuesta a emergencias de Manizales*). Decree 416, 23 August 2016 (in Spanish).

Barbat, A.H., M.L. Carreño, O.D. Cardona, and M.C. Marulanda. 2011. Holistic assessment of seismic risk in urban areas. *Revista Internacional de Metodos Numericos para Calculo y Diseño en Ingenieria* 27(1): 3–27 (in Spanish).

Barbat, A.H., M.L. Carreño, L.G. Pujades, N. Lantada, O.D. Cardona, and M.C. Marulanda. 2010. Seismic vulnerability and risk evaluation methods for urban areas. A review with application to a pilot area. *Structure and Infrastructure Engineering* 6(4): 499.

Bernal, G.A. 2014. Multi-hazard modelling of disaster risk in Manizales (*Modelación multiamenaza del riesgo de desastes en Manizales*). Technical report. Gestión del Riesgo – Manizales. Manizales: Corporación Autónoma Regional de Caldas (CORPOCALDAS) (in Spanish).

Bernal, G.A., M.A. Salgado-Gálvez, D. Zuloaga, J. Tristancho, D. González, and O.D. Cardona. 2017. Integration of probabilistic and multihazard risk assessment within urban development planning and emergency preparedness and response: Application to Manizales, Colombia. *International Journal of Disaster Risk Science* 8(3). doi:xxx.

Birkman, J., O.D. Cardona, M.L. Carreño, A.H. Barbat, M. Pelling, S. Schneiderbauer, and T. Welle. 2013. Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards* 67(2): 193–211.

Cárdenas, J.R.G., A. Nebot, F. Mugica, M.L. Carreño, and A.H. Barbat. 2015. Social aggravation estimation to seismic hazard using classical fuzzy methods. In *Simulation and modeling methodologies, technologies and applications,* ed. M.S. Obaidat, T. Ören, J. Kacprzyk, and J. Filipe, 275–293. New York: Springer.

Cardona, O.D. 2001. Holistic evaluation of the seismic risk by using dynamic complex systems (*Estimación holística del riesgo sísmico utilizando sistemas dinámicos complejos).* Doctoral thesis, Universidad Politécnica de Cataluña, Barcelona (in Spanish).

Cardona, O.D. 2004a. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: A necessary review and criticism for effective risk management. In *Mapping vulnerability: Disasters, development and people*, ed. G. Bankoff, G. Frerks, and D. Hilhorst, 37–51. London: Earthscan Publishers.

Cardona, O.D. 2004b. Curriculum adaptation and disaster prevention in Colombia. In *International perspectives on natural disasters: Occurrence, mitigation and consequence*, ed. J.P. Stolman, J. Lidstone, and L.M. DeChano, 397–408. Dordrecht, Netherlands: Kluwer Academic Publishers.

Cardona, O.D. 2011. Disaster risk and vulnerability: Notions and measurement of human and environmental insecurity. In *Coping with global environmental change, disasters and security: Threats, challenges, vulnerabilities and risks,* ed. H.G. Brauch, U. Oswald Spring, C. Mesjasz, J. Grin, P. Kameri-Mbote, B. Chourou, P. Dunay, and J. Birkmann, 107–121. Berlin, Heidelberg, and New York: Springer-Verlag.

Cardona, O.D, M.G. Ordaz, E. Reinoso, L.E. Yamín, A.H. Barbat. 2012. CAPRA - Comprehensive approach to probabilistic risk assessment: International initiative for risk management effectiveness. In *Proceedings of the 15th World Conference in Earthquake Engineering*, 24–28 September 2012, Lisbon, Portugal. Available at: http://www.nicee.org/wcee/ [Accessed July 4th 2017]

Carreño M.L. 2006. Innovative techniques for seismic risk assessment and management in urban centers: Ex ante and ex post actions (*Técnicas innovadoras para la evaluación del riego sísmico y su gestión en centros urbanos: Acciones ex ante y ex post*). Doctoral thesis, Universidad Politécnica de Cataluña, Barcelona, Spain (in Spanish).

Carreño, M.L. 2015. Evaluation of the social fragility and lack of resilience for the city of Manizales (*Evaluación de la fragilidad social y la falta de resiliencia, en la ciudad de*

Manizales). Technical report. Gestión del Riesgo – Manizales. Manizales: Corporación Autónoma Regional de Caldas (CORPOCALDAS) (in Spanish).

Carreño, M.L, O.D. Cardona, and A.H. Barbat. 2004. Methodology for the performance evaluation of the disaster risk management (*Metodología para la evaluación del desempeño de la gestión del riesgo*). Monography CIMNE IS-51, Universidad Politécnica de Cataluña, Barcelona (in Spanish).

Carreño, M.L., A.H. Barbat, and O.D. Cardona. 2014a. Numerical method for the holistic evaluation of the seismic risk based on the fuzzy sets theory. *Revista Internacional de Metodos Numericos para Calculo y Diseño en Ingenieria* 30(1): 25–34 (in Spanish).

Carreño, M.L., A.H. Barbat, O.D.Cardona, and M.C. Marulanda. 2014b. Holistic Evaluation of Seismic Risk in Barcelona. In *Assessment of vulnerability to natural hazards: A European perspective*, ed. D. Alexander, J. Birkmann, and S. Kienberger, 21–52. Oxford: Elsevier.

Carreño, M.L, O.D. Cardona, and A.H. Barbat. 2007a. A disaster risk management performance index. *Natural Hazards* 41(1): 1–20.

Carreño, M.L., O.D. Cardona, and A.H. Barbat. 2007b. Urban seismic risk evaluation: A holistic approach. *Natural Hazards* 40(1): 137–172.

Carreño, M.L., O.D. Cardona, and A.H. Barbat. 2012. New methodology for urban seismic risk assessment from a holistic perspective. *Bulletin of earthquake engineering* 10(2): 547–565.

ERN-AL (Evaluación de Riesgos Naturales – América Latina). 2011. *Probabilistic modeling of disaster risk at global level: Development of a methodology and implementation of case studies. Phase 1A: Colombia, México and Nepal*. Background paper prepared for the 2011 global assessment report on disaster risk reduction. Geneva: UNISDR. Available at: http://www.preventionweb.net/english/hyogo/gar/2011/en/home/annexes.html [Accessed July 4th 2017]

Jaramillo, N., M.L. Carreño, and N. Lantada. 2016. Evaluation of social context integrated into the study of seismic risk for urban areas. *International Journal of Disaster Risk Reduction* 17: 185–198.

Khazai B., F. Bendimerad, O.D. Cardona, M.L. Carreño, A.H. Barbat, and C.G. Burton. 2015. A guide to measuring urban risk resilience: Principles, tools and practice of urban indicators. Quezon, Philippines: Earthquake Megacities Initiative.

Lantada, N., J. Irizarry, A.H. Barbat, X. Goula, A. Roca, T. Susagna, and L.G. Pujades. 2010. Seismic hazard and risk scenarios for Barcelona, Spain, using the Risk-UE vulnerability index method. *Bulletin of Earthquake Engineering* 8(2): 201–229.

Marulanda, M.C., O.D. Cardona, and A.H. Barbat. 2009. Robustness of the holistic seismic risk evaluation in urban centers using the USRi. *Natural Hazards* 49(3): 501–516.

Marulanda, M.C., O.D. Cardona, and A.H. Barbat. 2010. Revealing the socio-economic impact of small disasters in Colombia using DesInventar database. *Disasters* 34(2): 552–570.

Marulanda, M.C., M.L. Carreño, O.D. Cardona, M.G. Ordaz, A.H. Barbat. 2013. Probabilistic earthquake risk assessment using CAPRA: Application to the city of Barcelona, Spain. *Natural Hazards* 69(1): 59–84.

Saaty, T. 1980. The analytic hierarchy process. New York: McGraw-Hill.

Salgado-Gálvez, M.A., D. Zuloaga, C.A. Velásquez, M.L. Carreño, O.D. Cardona, and A.H. Barbat. 2016. Urban seismic risk index for Medellin, Colombia, based on

probabilistic loss and casualties estimations. *Natural Hazards* 80(3): 1995–2021.
SISBEN (*Sistema de Identificación de Potenciales Beneficiarios de Programas Sociales*). Database of national government to provide subsidies to low-income people 2011. SISBEN, Manizales, Colombia.
Suarez, D.C. 2007. Development of risk and risk management indicators at urban level for diagnosis and planning in Manizales (*Desarrollo de indicadores de riesgo y gestión del riesgo a nivel urbano para el diagnóstico y planificación en Manizales*). Master thesis, Universidad Nacional de Colombia, Manizales (in Spanish).
Suárez, D.C. 2015. Vulnerability information analysis for the city of Manizales (*Análisis de información de vulnerabilidad en la ciudad de Manizales*). Technical report. Gestión del Riesgo – Manizales. Manizales: Corporación Autónoma Regional de Caldas (CORPOCALDAS) (in Spanish).
UNISDR (United Nations International Strategy for Disaster Reduction). 2009. *Global assessment report on disaster risk reduction: Risk and poverty in a changing climate*. Geneva: UNISDR.
UNISDR (United Nations International Strategy for Disaster Reduction). 2011. *GAR2011: Global assessment report on disaster risk reduction: Revealing risk, redefining developmen*t. Geneva: UNISDR.
UNISDR (United Nations International Strategy for Disaster Reduction). 2013. GAR2013: Global assessment report on disaster risk reduction: From shared risk to shared value; the business case for disaster risk reduction. Geneva: UNISDR.
Velásquez, C.A., O.D. Cardona, M.G. Mora, L.E. Yamin, M.L. Carreño, and A.H. Barbat. 2014. Hybrid loss exceedance curve (HLEC) for disaster risk assessment. *Natural Hazards* 72(2): 455–479.